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ABSTRACT. Design and application of multi-finger mechanical hands and robots in industry are discussed.

Handicrafts are a typical activity of humans in changing their surroundings in the technical sense. Industry was developed from handicraft activity, essentially by unifying the products and making them in mass production instead of individually. The production — technical side — was mostly based on handicraft work. Today, heavy work pieces are moved using cranes. Metal cutting manufacturing is no longer done with a chisel and a hammer, but with machine tools. Nevertheless, the human hand is an essential tool for human beings to deal with their surroundings.

At the beginning of this century, the first completely automatic mass production lines appeared. Today, completely automatic manufacturing without the intervention of the human hand is no longer unusual. Automata carry on this work and process computers control the functioning of the individual automata. Because of costs, this type of manufacturing without the intervention of human hands is reserved for processes in which a large number of pieces are manufactured. Just as before, small and moderate numbers of components are made using machines which are operated by the hands of the operators. Human hands also operate transport devices for transporting the materials between the individual machines.

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**Numbers in the margin indicate pagination in the original foreign text.

Whenever humans are replaced in a production line, the human thinking with the sensory aparatus, as well as the hands, must be replaced. In a production chain in which the work is divided up, only a small amount of thinking is necessary. The entire brain structure is only used to detect a deviation from the requirements and for orientation purposes.

The range in which humans must apply the brain has been severely restricted by the introduction of process control computers and numerical machine controls as well as technical sensors for taking measurements in the surroundings (for example, remote television surveilance systems, light barriers, non-contact magnetic sensors, and similar devices.) Already today, it is technically possible to completely eliminate from the production process the cognition and thinking part of human thinking as far as the execution and surveilance functions are concerned. Therefore, we are able to use foreign workers with a little training in our production facilities without any technical difficulty. They also do not know our language. We only use their hands as the working tools.

Parallel to this development or as a consequence of this goal of using human work not as a part of the automata chain, but as an individual and dignified activity, a large number of constructions have appeared on the market which are intended to replace human work by hands. These are the industrial robots which use technical hands and, by means of numerical control, can replace humans if only the two following human characteristics are involved:

— an easily programmable program unit,
— universal gripping tools which are not only controlled by this program unit, but whose gripping functions can also be modified depending on observing reality.

Our hands are so much an unconscious working tool with the surroundings that a great deal of thinking is necessary to realize their full potential and to develop construction characteristics for technical hands from this knowledge.

The goal of physiological studies has been to find the optimal matching between human hands and technical tools. Many investigations have been carried out on the type of manipulations that humans can carry out. Let us first realize the capacities of the human hand. The hand consists of the hand surface and the fingers. The lower arm is an important part of the hand, because all "drive motors" for the many motion possibilities of the fingers are located in the lower arm. Tendons (tackle) connect the point of motion with the point where the force is produced. This is why a relatively high degree of performance at the point of motion can be obtained together with a relatively narrow and fine method of construction. There are no disturbing motor systems present. In addition, there is a greater degree of protection for the tendons with this method of construction. This is why, when the hand surface is injured, only the muscles and not the driving motors are replaced. The muscles are really not of primary importance for the motion itself. The tendons are protected and lie below the muscle groups. Mechanically, they have greater resistance than the muscles above them.

The hand is capable of carrying out three fundamental types of manipulations:

— Embracing manipulations in such a way that all fingers are bent together or individually around a cylindrical object.

— Enclosing manipulations, which are produced by spreading the individual fingers at the base so that they enclose a spherical volume after bending. In this way, round objects can be gripped and held.

— The third class of manipulations includes the flat-hand gripping motions, for example, the pushing off and supporting motions. These manipulations have a relatively large support area. For example, this is used to shovel sand or to perform similar functions.

A total of almost one hundred technical working manipulations can be defined. They differ slightly in terms of their elements, and the use of the

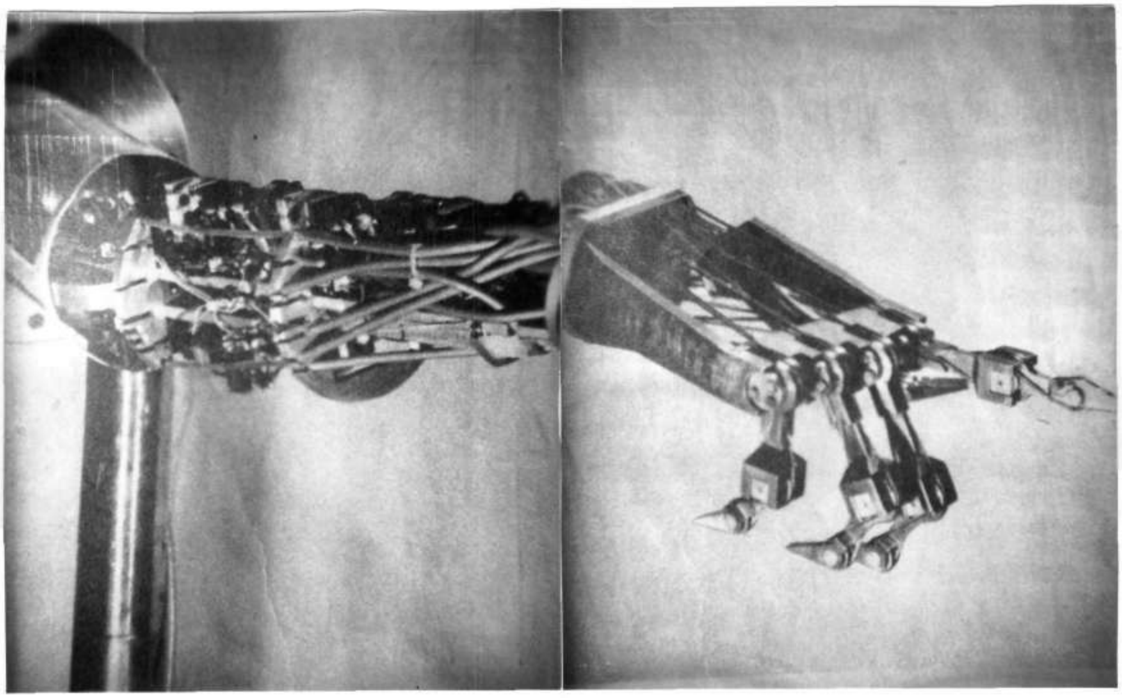

Fig. 1. Five finger grasping hand. (Photographs from Kybertronik GmbH & Co., KG, Rossdorf.)

individual fingers varies. The technical construction (Figure 1) of the human hand with 15 joints (which have a total of 22 individual degrees of freedom) is extremely laborious. First of all, the question is raised of whether this is necessary for performing technical work. Extremely complicated hand motions (for example, piano playing) do not belong within the realm of technical work. In most technical applications, the universal nature of the human working hand is not required.

An investigation of the technically realizable manipulations shows that a hand having only one finger (surface with movable part) could perform about 5% of all the manipulations. If two movable finger parts are used, then the totality of possible manipulations is increased to about 40% (Figures 2 and 3). If a third freely movable finger is added (having the same degrees of freedom as the human hand), then almost 90% of the possible technical manipulations can be performed (Figure 4). A four-finger hand increases the technical manipulation possibilities to about 99%. A fifth finger, on the other hand, only extends the manipulation range by about 1%.

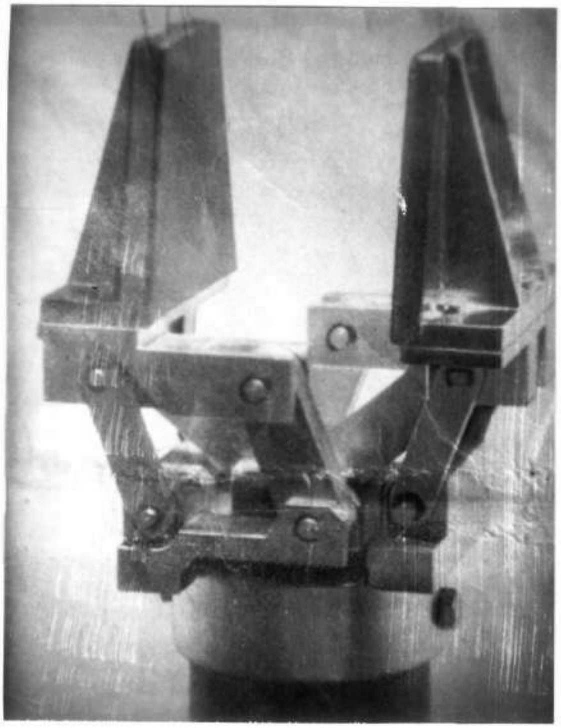

Fig. 2. Two finger grasping hand (grasping pliers).

Fig. 3. Compressed air controlled manipulator with two finger hand.

It is clear that three fingers can perform most of the technical manipulations (Figure 5). However, in the human hand, three fingers still have nine joints and twelve different degrees of freedom. Even this amount of effort seems relatively high. It is interesting to see what happens when we restrict the manipulation possibilities of these three fingers further (if, for example, only two free joints are placed on each finger instead of three). Then, we obtain six joints for the three fingers. If the degrees of freedom of these three fingers are reduced to seven, then the capacity of this hand is reduced to about 50% of the possible manipulations.

A more exact investigation of the problem shows that it is not the number of joints which influences the possibilities of the hand, but it is the number of the degrees of freedom. From this a compromise can be reached by adding additional degrees of freedom to the natural degrees of freedom of the joints (this solution will deviate from the natural solution). This extends the

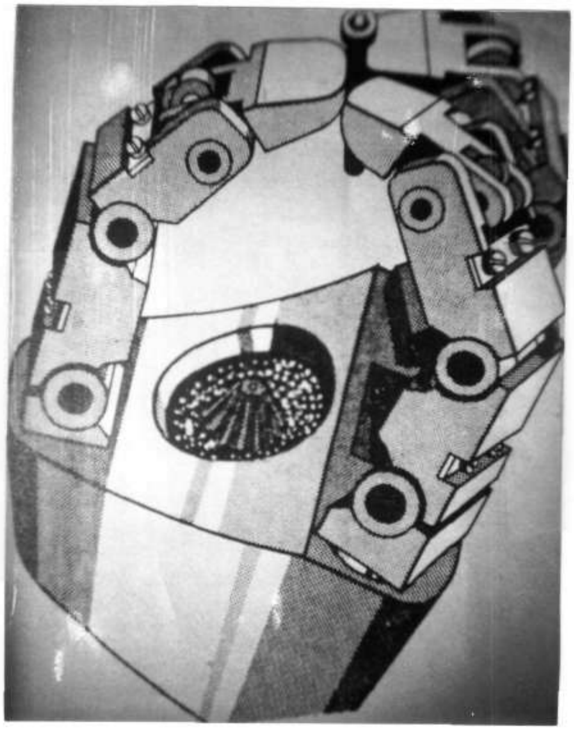

Fig. 4. Three finger hand.

technical manipulation range of this mechanical hand.

75% of all technical manipulations can be obtained with the following technical construction. An additional rotary joint is introduced at the base of the technical fingers which correspond to the human second finger and middle finger. By means of these, it is possible to rotate the inclination planes of the fingers with respect to each other. An additional joint (that cannot be driven freely by a motor, but is controlled by the second joint) only serves to bend the bent contour of the finger in a better way than is be possible by simple buckling. An investigation showed that, if two manipulations are carried out, one after another using this mechanical hand, it is possible to perform 89% of the possible manipulations.

A hand built according to this construction has four joints per finger for the middle and second finger (the bases of which are separated more than in the case of a human hand). Of course, the three joints can be controlled in an arbitrary fashion. The fourth joint is automatically controlled by the second joint. The greater base distance makes it possible for the thumb to fold out of the working area between the middle finger and the two index fingers. A turning joint construction similar to that of the natural hand would encounter serious difficulties for this thumb as far as strength and movability are concerned. This is based on the fact that technical versions of joints work on simple geometric surfaces. On the other hand, the joints of the human hand use sliding surfaces which, in part, are deformed during the motion. Also, the human hand has extremely complicated gliding joints which are continuously lubricated with the joint liquid and have an exceptional

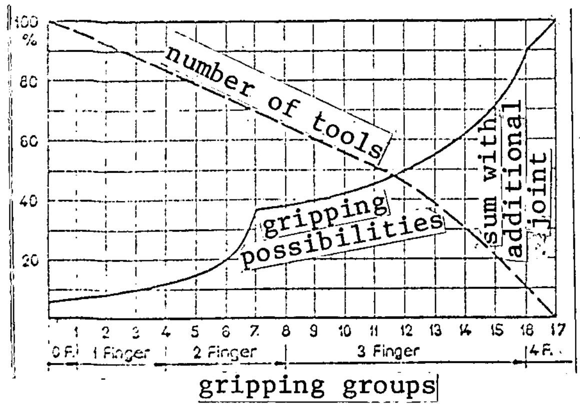

Fig. 5. The influence of the number of fingers on the gripping possibilities.

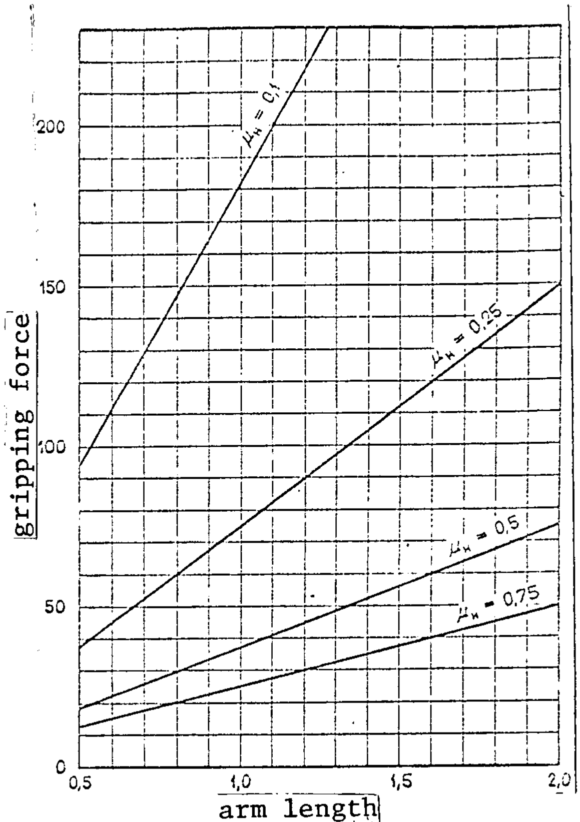

Fig. 6. Dependence of the gripping force on the arm length and the adhesion friction coefficient.

safety system with pressure and force sensors. This kind of effort is not justified for a mechanical hand.

The manipulating force per finger of the natural hand lies between 3.5 and 5 kp at the finger tips. It is about 25 kp for all fingers working together. The requirement for replacing the human hand by a machine hand in the production process requires the same force as the human hand possesses. An investigation showed that it is not appropriate to make use of the greater strength of the material of the mechanical hand in order to transfer larger forces. The same mobility as in the natural hand only remains if only small forces are transferred. A disproportionate amount of effort would have to be expended in the design of joints for large forces. Therefore, it is must more appropriate to use plier-like, two-finger hands for large manipulation forces. These have been used in nuclear power plants for a long time. It then becomes possible to transfer considerably larger forces (up to 10 times the natural force) without compromising the design. The motion possibilities are the same as for the natural hand. However, one knowingly gives up the various motion ranges of the working hand (Figure 6).

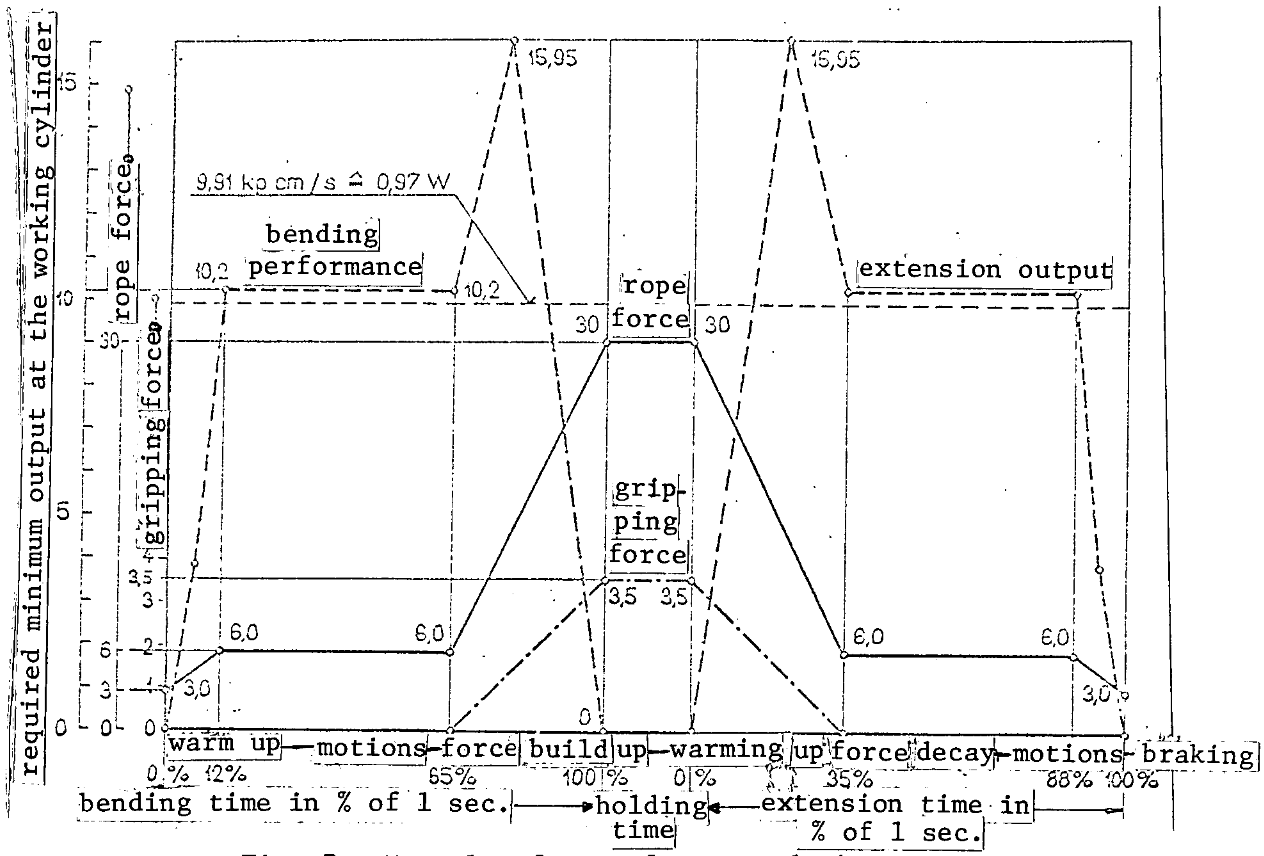

Fig. 7. Example of a performance design.

A maximum velocity of 45° per second has been found appropriate for the working hand. The human hand cannot continuously perform at a higher level. If this angular rate is maintained, then the wear of the technical system is still relatively small and the acceleration forces can be controlled (Figure 7).

In addition to its capacity for work, the human hand also has sensors with which to interact with the surroundings. Essentially, these are the feeling receptors, as well as the heat and cold receptors. The machine hand must also have receptors so that it can determine that it has made contact with an object. It must be able to feel contours. It is also convenient for it to have heat receptors. With these, it can measure dangerous temperature influences for the work process or for the material it is handling. Also, seized bearings can be detected by their heat production and can be detected using the same receptors. The pressure receptors, which are used for feeling, can also be used as force measurement devices. This brings about a control of the manipulation forces: then the human hand manipulates an egg differently from a lead sphere.

If we consider the numerous receptors distributed over the human hand (these amount to several 10^5), then it becomes immediately clear that it will never be possible to build technical working hands of this order of magnitude. A relatively small number of receptors give only a coarse point raster picture of reality. Therefore, the feeling performance is not comparable. However, mechanical hands have a processing apparatus designed according to another concept which can equalize the disadvantages in the receptor distribution. The mechanical hand we built has twelve receptors per finger. The signals of these are sufficient to measure the manipulation force on the one hand, and also to give a rough orientation in the surroundings (for example, it can detect corners, can run along surfaces, can determine structure symmetries, etc.) without the use of the human eye.

In any practical working process, the receptors of the mechanical hands must primarily determine whether a program deviation has occurred or not. This state of affairs must be communicated to the central unit which directs the work. Because of their task, mechanical hands operate in a known environment and therefore unexpected conditions only occur with an error. Such an error must be signalled under all circumstances. It is not always necessary for the control system of the hands to control this error. This restriction considerably simplifies the overall technical effort for the control system and the receptors.

When humans solve a problem by grasping something, then they are only conscious of the final process which is the object. They no longer are conscious of the individual motion elements which led to the final result. In the case of humans, this is programmed by means of a lengthy learning process in such a way that all motion elements are tuned to each other in the form of a motion chain which is well organized. Small children learn to grasp objects with their hands at various distances. They learn manipulations for round, long and thin objects. When this learning phase is over, there is a fixed program in the nervous system for the individual motion elements in such a way that certain motion chains will automatically occur one after the other. Also, various related motions are synchronized to this chain.

The total manipulation process is first decomposed into signals in a first and upper plane. These signals determine which elements should be activated. The individual motion elements themselves are then activated in a second logical program. The final manipulation is produced by means of an additional synchronization control system (i.e., by adjusting the pressure forces and manipulation forces between these elements). The organization of such subordinate information processing functions (which are autonomous themselves, but which influence each other) are called hierarchically organized information processing.

In order to use mechanical hands in technical fields, it is extremely necessary to perform hierarchically organized processes. It is possible to either carry out programs with a process control computer or to use hard-wired programs in conjunction with a specially designed numerical control system. Which of these alternatives is more advantageous depends not so much on the task , but on the additional boundary conditions.

The individual motion sequences in a technical working system are controlled by means of an independent task control circuit unto which a force limitation is superimposed. An additional control system synchronizes the individual bearing control circuits and produces manipulation patterns instead of individual motions. A selection controlled system which is superimposed deciphers a digital command word produced by the central control system. This results in the individual motion patterns and activates them. The task control circuits are of the analog type because the equipment associated with this design is less complicated. Also, the force limits can be introduced more easily by means of the analog system. The sychronization is done digitally. There is an analog-to-digital conversion between these two planes. The motion pattern /45
control system is purely digital and uses the BCD code. It can be directly controlled by means of a process control computer.

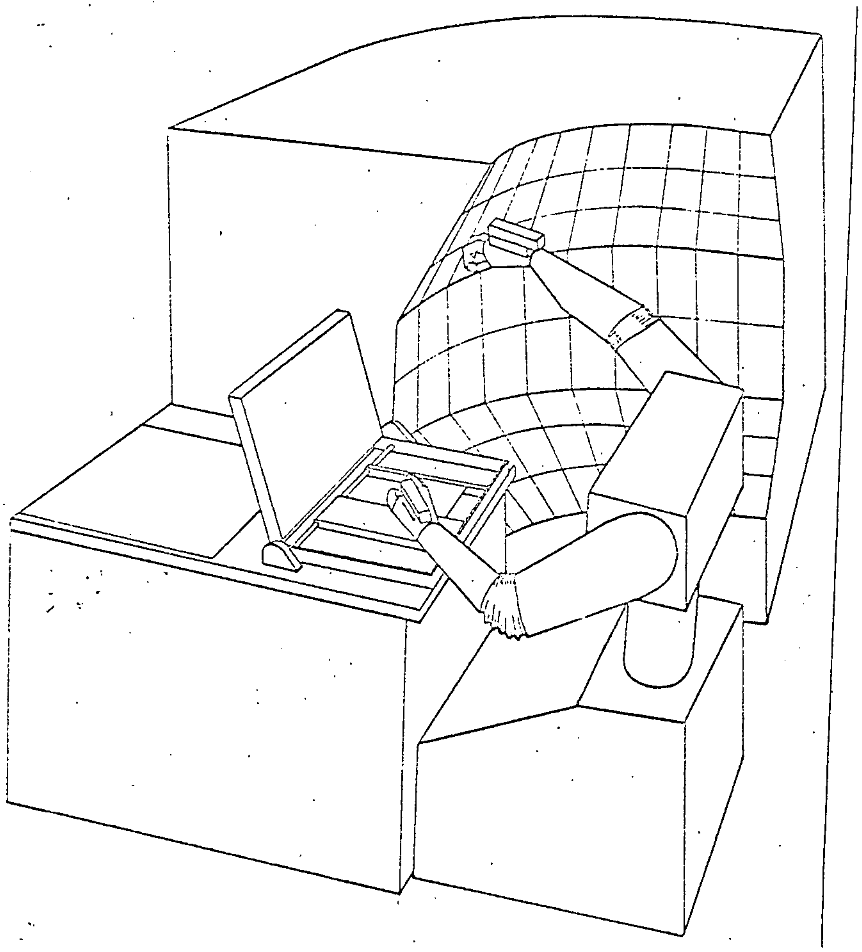

Fig. 8. Two arm gripping robot at a work station.

New developments will make it possible to house the entire control electronics and the drive systems in the lower arm of a three finger mechanical hand. However, the working energy must be provided in the form of either mechanical or hydraulic energy. Electromechanical or electrohydraulic converters take up too much space and cannot produce the required amount of output within the available system. Of course, it is not disadvantageous for a mechanical working hand to have a type of "umbilical cord" coming out of the elbow which would be used for supply of energy. This set of circumstances limits the use of such technical mechanical hands as artificial limbs. This also explains why artificial limbs really capable of performing work are either bulky or have insufficient performance capabilities.

A working robot consists not only of the working hands, but also of the arm system which moves the hands in space. There are many variations of the superimposed hand control of this entire robot system. It depends strongly on the problem to be solved and cannot be given in general terms.

Summarizing, we may say that over 75% of all technical working manipulations can be carried out by means of a three finger working hand, which is similar to a human hand as far as fineness and force transmission at the point of motion are concerned (however, it deviates strongly as far as the joints and position of the individual joint surfaces are concerned). By coupling the system with suitable sensors, the same safety in motion in unknown surroundings can be provided for as if a human hand were being used. The control of these working hands can have various degrees of complexity and therefore also have different performance levels. There is no technical necessity of using humans only as manipulation robots in a production process. Working robots and automatic mechanical hands will make it possible to remove humans from a hostile, unfriendly and degrading work environment (Figure 8). Humans can then be used for work in which they have to apply their thinking and cognitive functions.

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